Gail Purvis

The UCSB Santa Barbara location suited the North American Molecular Beam Epitaxy conference, with its relaxed, close-knit community. Sitting outside the amiably small airport, waiting to depart, after the conference, Ravi Droopad, Distinguished Member of Freescale Semiconductor technical staff reflected that NAMBE had been workshops and changed considerably, with the 2005 meeting, unlike earlier ones, showing in its attention to oxides and advanced material, the pressures now facing dead-end silicon.

MBE: on the light side

But the NAMBE community seems less pressured, and those who turn out of mainstream MBE work are mourned, briefly, as "joining the dark side."

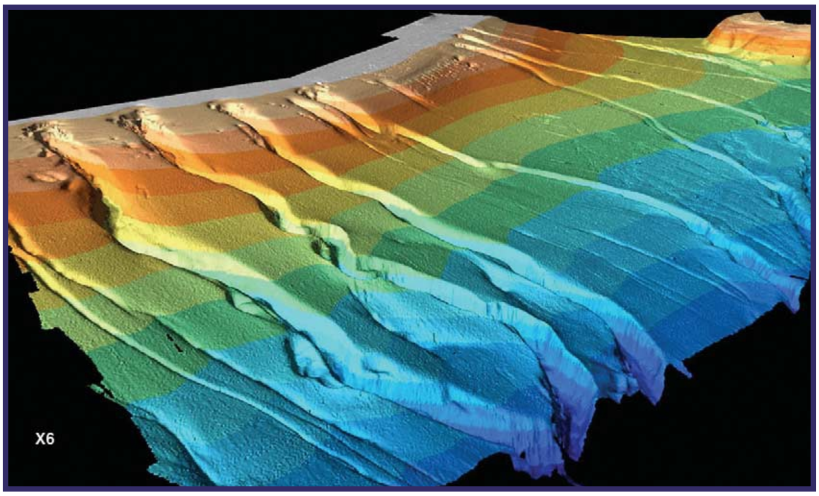
In his opening talk on oxide heterostructures, James Eckstein, at the physics department of the University of Illinois, noted that complex oxides exhibit a wide range of physical properties in structurally similar compounds, and that those with perovskite structure are a particularly interesting set.

In bulk these exhibit superconductivity, ferroelectricity and a number of spin, charge and ordered electronic phases. Many have lattice constants in the range of 3.9 ± 0.1 Angstrom.

"We have found this to be a small enough range that fully strained heterostructures involving different compounds can be assembled."

He pointed out that strain, local charge transfer, and the disruption of long range crystalline order can lead to systematic modification of physical properties at such interfaces. Dielectric superlattices, with broken inversion symmetry, can develop a built-in polarisation due to asymmetric strain relaxation. Particle hole symmetry in cuprate superconductors, occurring in bulk, is broken at an interface to an insulator. Manganite superlattices, imposing crystalline order, quenches bond ordering and anti-ferromagnetism.

In all cases ordered phases are modified on mesoscopic length scales by proximity to dissimilar materials. The results show that emergent collective phenomena can be systematically engineered in a way similar to how band structure engineering works in semiconductor systems giving rise to new phenomena and the potential for new devices.



Santa Barbara like some rare colourful compound material. Courtesy: Monterey Bay Aquarium Research Institute (MBARI) Bounded in 1987 by David Packard. Http://www.mbari.org/data/mapping/SBBasin/images/santabarbarab_perspective.jpg

Rare earths and oxides

Papers covered "strained $SrTiO_3$ and $BaTiO_3$ films having better structural perfection than single crystals (D G Schlom *et al* in *Enhancing ferroelectrics using strain*); the design and material parameters of *Epitaxial growth of $BaTiO_3$/Sr TiO_3 and BaO/$SrTio_3$ superlattices for phonon confinement* (Arsen Soukiassian et al from Penn State, CABIB, Argentina, Michigan, Rutgers, Valencia and Puerto Rico Unversities) show an enormous stop band compared to the GaAs/AlAs semiconductor superlattices previously reported; and *MBE growth of $YMNO_3$ on GaN* was covered by Y Chye *et al* West Virginia Unveristy.)

Freescale's Ravi Droopad talked about gate dielectrics and the 20-year search for MOSFETs based on compound semiconductors, where unlike silicon, these do not possess a suitable native oxide for low interface state densities required for MOSFET device fabrication.

In his group's research presention, the use of MBE in the development of $(GdxGA1\text{-}x)_2O_3$ /Ga_2O_3

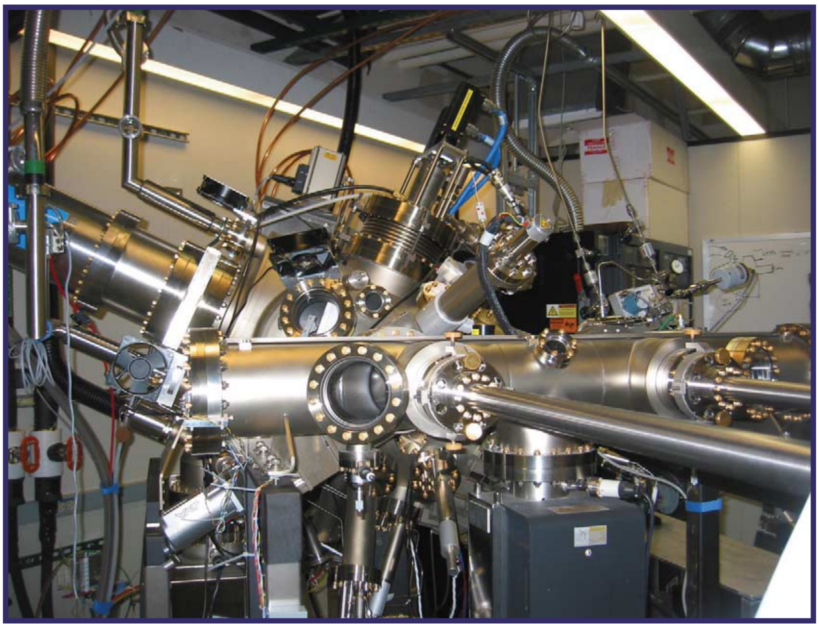
based multilayer gate dielectric on GaAs that result in unpinned Fermi level, has the required properties for the fabrication of GaAs MOSFET devices and PHEMT-based MOSFETS have been grown with $(Gd_xGA_{1-x})\ _2O_3/Ga_2O_3$ dielectric stack and mobilities determined using a contact-less Hall measurement technique. Room temperature mobility sin excess of 6000cm^{2}V^{-1}s^{-1} with carrier concentration of 2-3x10^{12} cm^{-2} have been measured, which compared favourably with Hall measurement on PHEMT devices without the oxide layer and it appears that Freescale is funding research in this area.

Advanced materials

This section covered: *ErAs island stacking growth technique for engineering textured Schottky interfaces* (J D Zimmerman *et al* , UCSB); *MBE of ErSb on GaSb* (S G Choi *et al* University of Minnesota); MBE growth of III-V superconductors containing epitaxial semimetallic nanoparticles for thermoelectric power generation (Joshua M Zide *et al* UCSB, UCB and UCSC); MBE growth of Osmium silicides (RJ Counter *et al* Unversities of North Texas and Houston); and crystalline stability of congruent and Li-Rich lithium niobate for a new substrate for III-nitride optoelectronic-acoustic-electronic applications (Gon Namkoong *et al* of Georgia IoT; Bari Univeristy, Italy and Crystal Technology Inc).

III-Vs growth and mismatched growth

Papers her includes: *How adatom dynamics lead to smoothing of patterned surfaces in GaAs homoepitaxy* (Anders Ballestad *et al* University of British Columbia); *develo-pment of 6.00A graded metamorphic buffer layers and high performance In0.86A10.14As/ In0.86Ga0.14As HBT devices* (A Cavus *et al*, Northrop Grumman Space Technology and UCLA); *Relaxation kinetics and dislocation interactions on III-V metamorphic buffer layers* (B Perez Rodrigues *et al*, University of Michigan) ; *Suppression of surface segregation of silicon dopants during MBE of (411)AInO.75Ga0.25As/ In0.52A10.48As pseudomorphic high electronmobility transistor structures* (H Sagisaka *et al*, Osaka University, NIICT and Fujitsu Laboratories); and *Metamorphic growth of InP on GaAs by MBE for mode-locking fibre laser application* (S Suomalainen, Tampere University of Technology and University of Twente, Netherlands).



Highlight of the NAMBE conference was being shown round the UCSB MBE empire of some eight machines

Nitrides, magnetics and ZnO

The opening paper portrayed MBE solidly as a production tool rather than simply agile R&D equipment. Ben Heying *et al* from Northrup Grumman Group discussed work *optimising and scaling the MBE growth to produce high quality and highly uniform Gan based HEMT structures.*

Some MBE parts were endearingly wrapped in heavy foil for 'bake' work. Onlookers saying that the heavy duty foil was bought in the supermarket!

An MBE for all seasons: nitrides, ferromagnetics, spintronics and the promise of 'way more MBE growers.'

"We have found the material properties to be extremely sensitive to substrate temperature and Ga/N ratio. By optimising these growth parameters we have been able to achieve transistors with electron mobilites in excess of 1700cm^2/Vs.

"Using optimised material we have fabricated T-gate devices that have output powers of 4.1W/mm with 41%PAE at 32GHz. However due to the narrow growth window it has been a challenge to achieve the uniformity and repeatability for larger diameter wafer."

The discussion covered efforts to reduce materials variations as the growth process moved from 2" to 3" diameter wafers and the current challenges and limitatations of scaling the growth of GaN to larger production tools.

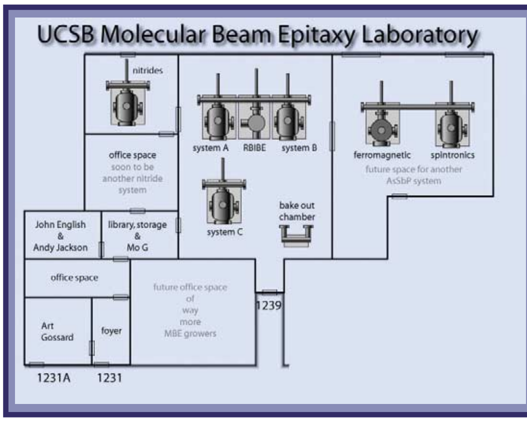
OMVPE speaks up

Sandia National Laboratories' Andrew Allerman, took his courage in both hands, braving the pride of MBE, with his talk on *The growth of nitride materials: a perspective from the OMVPE camp* - which drew not a little laughter.

"The dominant growth technology employed in fabricating LEDs and diode lasers is the OMVPE process, in spite of a number of challenges in reactor design and source chemistry." He reviewed the challenges and advances of OMPVE nitride growth technology. "While the lack of native substrate results in films with high dislocation densities compared to other compound semiconductor, the OMVPE growth of GaN affords a number of approaches to generating faceted growth, that can be used to reduce threading dislocation density."

A major challenge faced by OMVPE is that of parasitic gas phase chemical reactions between typical metaloraganic sources and ammonia. The nature of these reactions and the means to reduce them in the growth of GaN and AlGaN film was discussed.

Nitride I covered growth and characterisation of GaInN (W J Schaff *et al* Cornell Unv., LBNL, and UCB); *MBE growth of InN* (Chad Gallinat *et al* UCSB); *Development of UN-LEDs based on III-nitride MQWs grown along non-polar [11-20] directions* (Ramya Chandrase-karan *et al* Boston and Arizona State University).*Reaction of MBE grown AlN nucleation layers with SiC substrates* (W E Hoke *et al*, Raytheon RF Components); *Prospects for room temperature ferromagnetic bulk GaMnAs* a late stand in paper (R P Campion *et al* University of Nottingham, Hitachi Cambridge Lab, University of Cambridge, Texas A&M University and IoP ASCR, Czech Republic); *High power UV-LEDs grown by PAMBE* (Jasper Cabalu *et al* Boston University and US Army Research Laboratory); *Bulk-like properties of densely-packed GaN nanocolumns grown by MBD* (K L Averett *et al* Air Force Research Labs and NIST); *Growth of thin AlInN/GaInN quantum wells for*



Courtesy: http://www.materials.ucsb.edu/~mbe/lablayout.html The layout of the amazing MBE kingdom at UCSB which clearly grows and changes machines and their materials relentlessly

application to high speed intersub-band devices at tele- communication wavelengths (G Cywinski ***et al*** from Academy of Sciences, Poland and Univ Paris S.)

Magnetic materials covered ***Spin VCSEL epitaxial growth issue sand device properties*** (Mike Holub, Univ. of Michigan); ***Growth of paramagnetic GaMNAs and In GaMnAs QWs for optical spin spectroscopy*** (Robert C Myers ***et al*** UCSB); ***MBE growth of Ge-based magnetic semi-conductors*** (Frank Tsui ***et al***, Univ. of N. Carolina CH, Argonne Nat. Lab); ***Mn doping of GaAs QWs and QDs in ultra dilute limit*** (Mark White ***et al*** UCSB) ***MBE growth of single crystal*** Co_2MnGe ***on*** $SrTiO_3$ ***(001) and MgO (001) substrates*** (S K Srivastava, Univ. of Minesota, Penn State and Yale).

ZnO thin on the ground

For ZnO, ***RF power dependency on ZnO films growth by PAMBE*** (W C T Lee ***et al*** McDiarmid Inst. for Advanced Material a& Nano technology, New Zealand); ***P-type ZnO films by Sb doping in MBE*** (F X Xiu ***et al*** UC Riverside); and ***fabrication of Mg ZnO-ZnO-AlGaN heterostructures for UV LED applications by novel ozone assisted MBE*** (R Hartmann ***et al***, SVT Associates Inc).

On the last day, QDs, dilute nitrides and devices aire with ***High performance, self-organised In(Ga)As QD lasers on silicion*** (Z Mi ***et al***, Univ. of Michigan) ***Size evolution of site controlled InAs QDs grown by MBE on pre-patterened GaAs substrates*** (P Atkinson ***et al*** Cambridge Univ.) ***Growth optimisation of In GaAs quantum wires for IR photodetector applications*** (Chiun Lug Tsai ***et al***, Univ. of Illinois, UC) ***Single state InAs/ Ga As QD IR photodetectors grown by MBE*** (D Pal ***et al***, Carnegie Mellon Univ.); and ***Facet formation of MBE-grown self-assembled InAs QDs*** (R Suzuki ***et al***, Fujitsu Labs)

Devices included ***MBE of AlGaAsSb-based VCLs*** (David Buell, UCSB); ***Type II W structure for mid IR LEDs operating cw at room temperature*** (Vladimir Kuznetsov ***et al*** Univ. of Rochester) ***Effects of doping on performance of QD-in-well photodetectors*** (R S Attaluri Unv. New Mexico); ***Fabrication and MBE regrowth of first order high contrast AlGaAs/ GaAs gratings*** (Chad Wang, ***et a***l UCSB) ***InAs/AlSb HEMT by MBE for low power applications*** (M D Lange ***et al*** Northrop Grumann ST, Naval Research Lab, & UCLA); ***Non-stoichiometric growth and precipitation formation in LTD-GaAsSb for THz applications*** (J Sigmund, Inst. for HFEI, FSFM, and IH Tech Univ. Braunschweig, Germany); ***Growth and characterisation of THz quantum cascade lasers*** (Maxwell Andrews ***et al,*** Tech. Univ., Vienna, Austria); ***High performance GaAsSbInP double HBT grown by gas-source MBE*** (Bing Ruey Wu ***et al***, (Univ of Illinois U-C).

To be published in: '*The Journal of Vacuum Science and Technology B*'